Phase Mask Coronagraphy: Scientific Results and Perspectives

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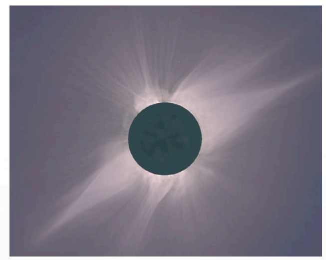
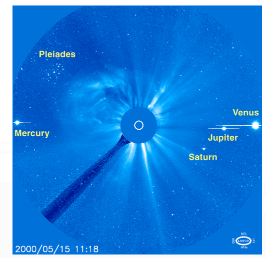
Phase Mask Coronagraphs

Introduction

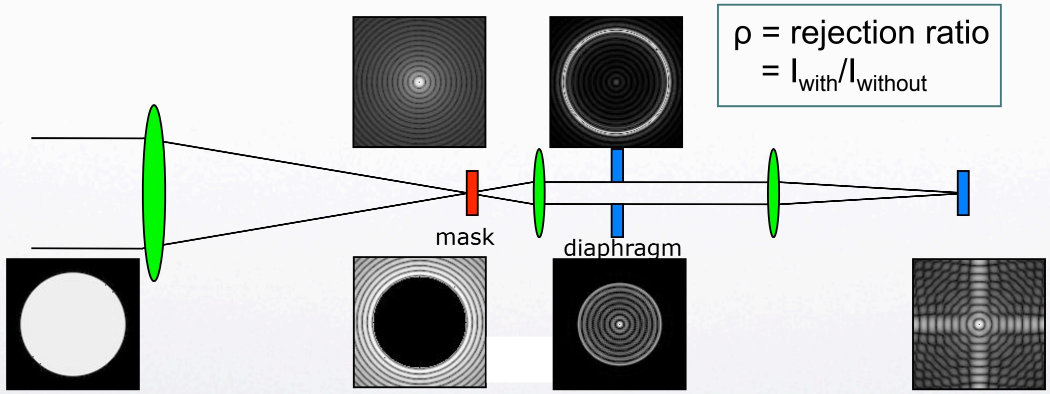
- Coronagraph

Solar corona without eclipses
→ coronagraph (Lyot, 1930)





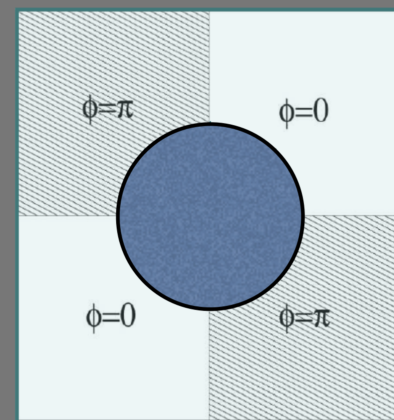
ρ = rejection ratio
= $I_{with}/I_{without}$

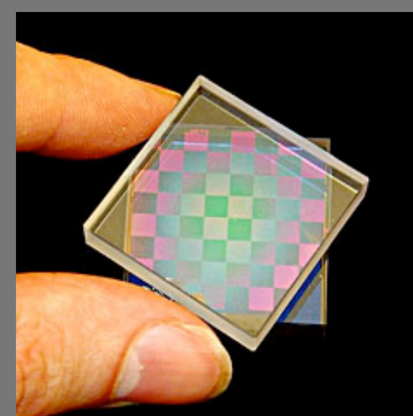


- Playing with the phase instead of amplitude (Francois Roddier's idea)

FQPM: a success story (Rouan et al. 2008)

- From Francois Roddier's idea, through Antoine Labeyrie and Daniel Rouan's discussion, the four-quadrant phase-mask coronagraph was born (Rouan et al. 2000);
- Lab extensive demo:
  - Optical, laser: 10^{-7} contrast at $3\lambda/d$ (Riaud et al. 2003)
  - Optical, broadband (20%): 10^{-7} at $4\lambda/d$ (Baudoz et al. 2007)
  - Optical, broadband (60%): 10^{-5} at $4\lambda/d$ (Mawet et al. 2006)
  - Near-infrared, broadband (3 x 20%): 10^{-4} at $3\lambda/d$ (Boccaletti et al. 2008)
  - Mid-infrared, broadband (10%): 5 10-5 at $3\lambda/d$ (Baudoz et al. 2005)





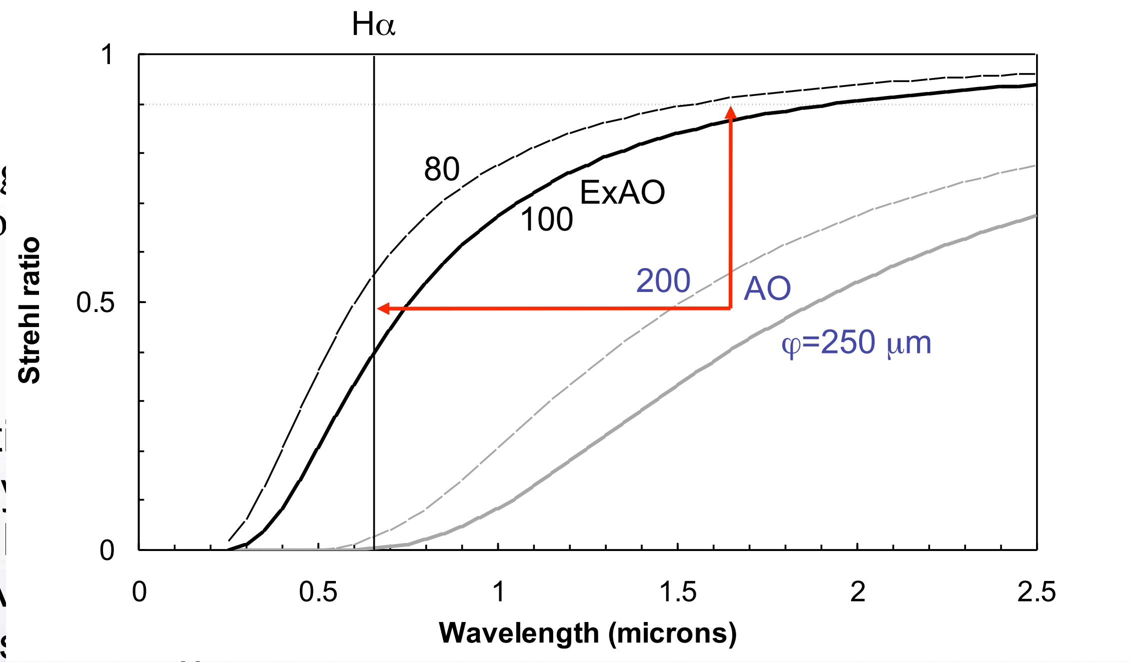
Success story

- Installed at NACO's focus since 2003 (VLT, Boccaletti et al. 2004)
  - two FQPM:
    - monochromatic H-band
    - monochromatic K-band

- Installed at WCS' focus since 2005 (Palomar):
  - several K-band FQPM

The Palomar "well-corrected subaperture" (Serabyn et al. 2007)

Existing
Telesco
Optics:

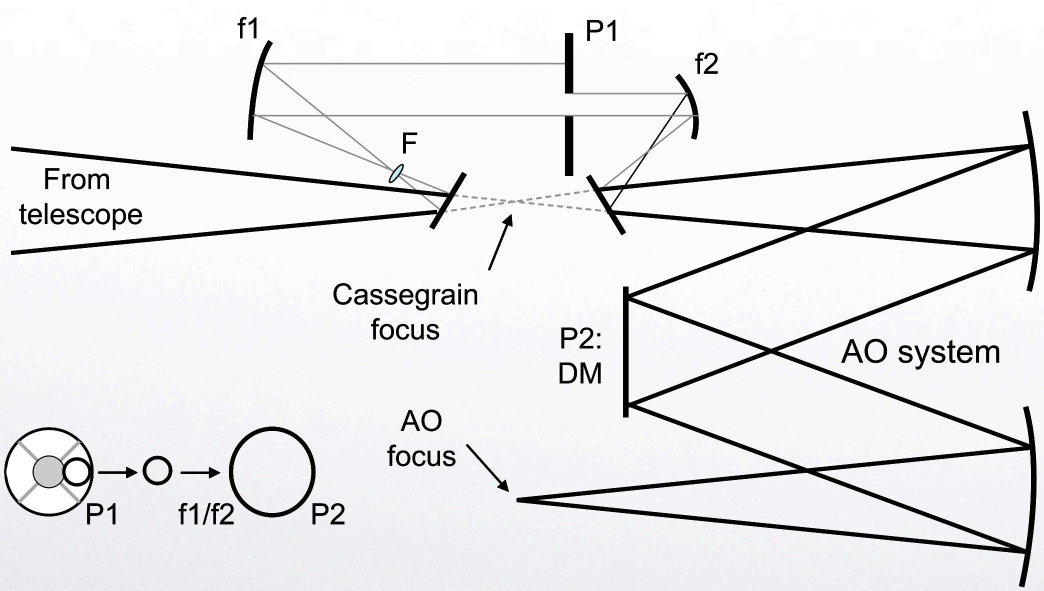


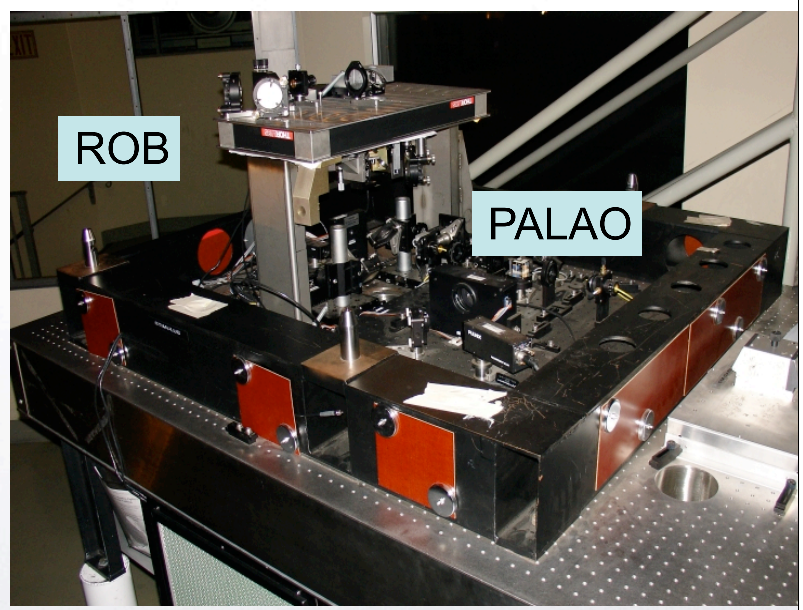
Camera

- Keep pupil locati
- Magnify pupil (b
- Center sub-pupi
- Maintain F# to A

⇒ post-AO optic

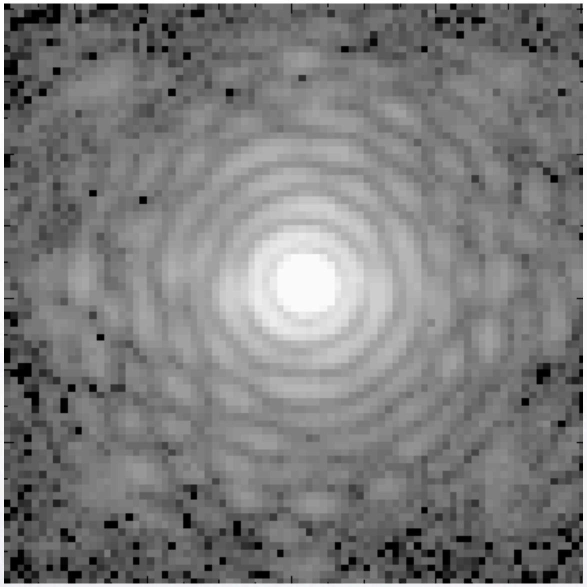
The Palomar "well-corrected subaperture"

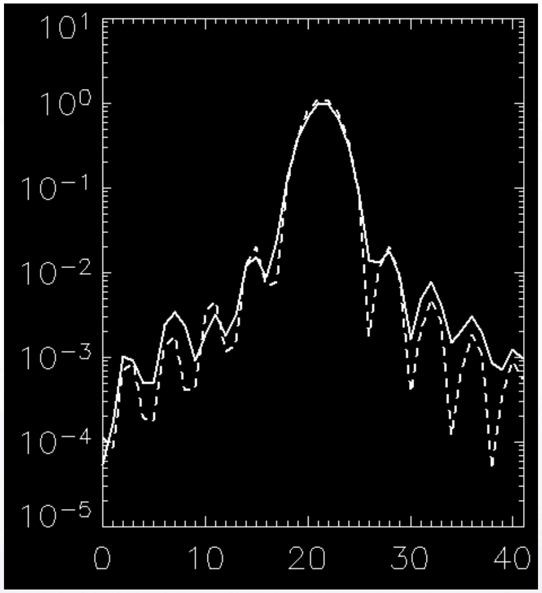


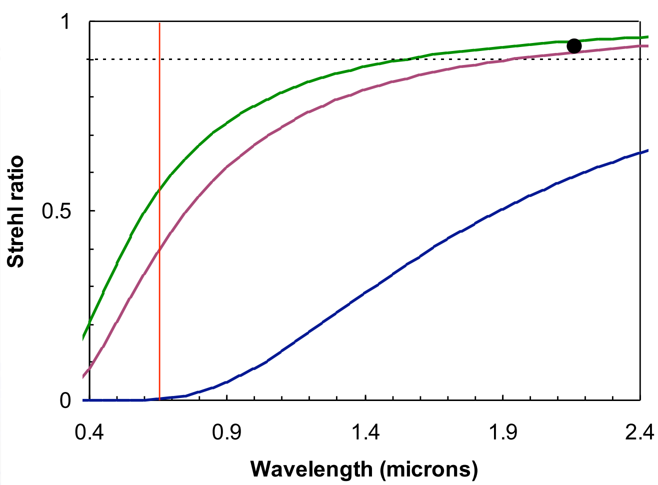


Performance

Results: Single star HD121107 in Br γ filter (2.17 μm)





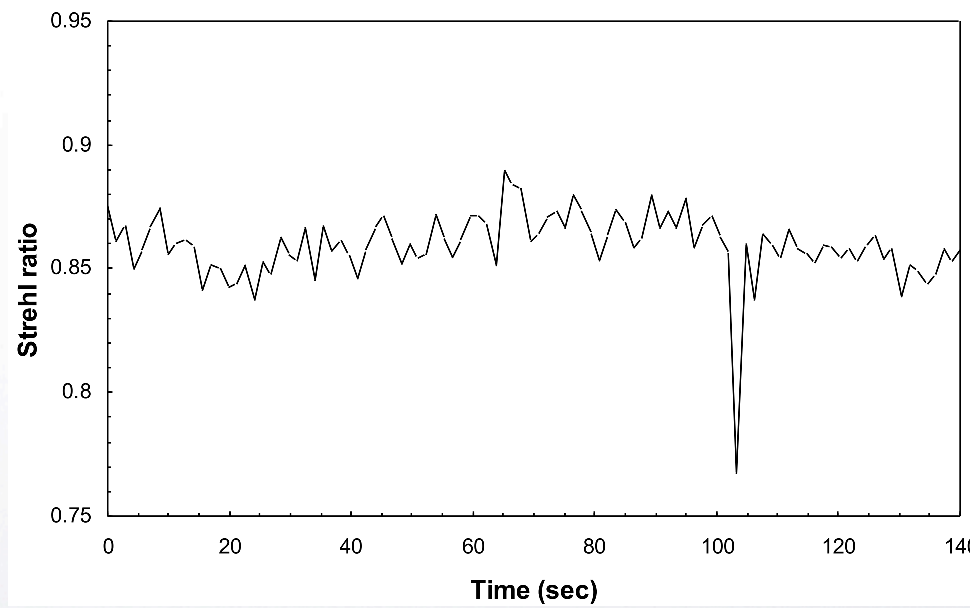


Sum of 20 exposures (log scale)
Integration time = 20 x 1.416 s
(center saturated for better view)

Performance

- Best Strehl ratio ≈ 0.92-0.94
- rms ≈ 85 -100 nm

- Strehl stability: 1 % rms

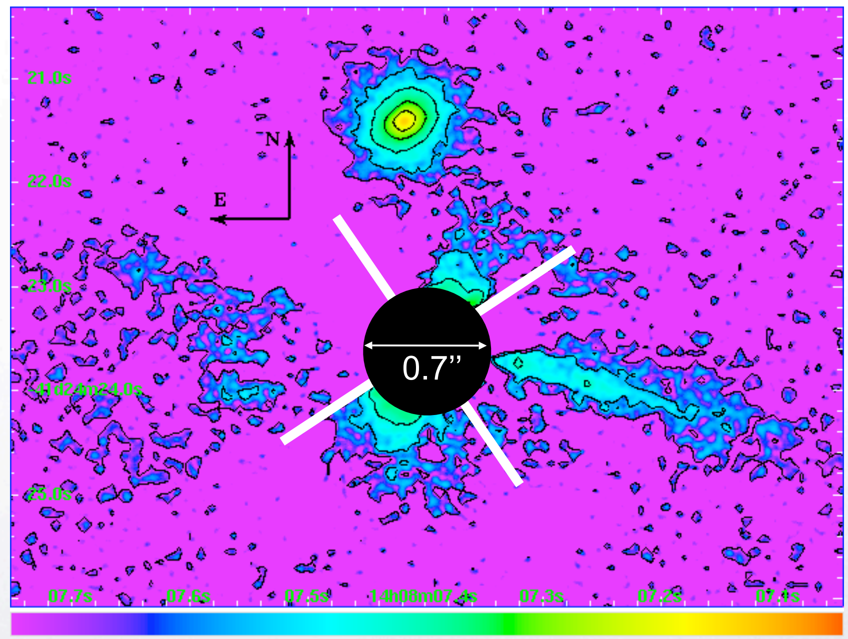


Scientific results

On NACO

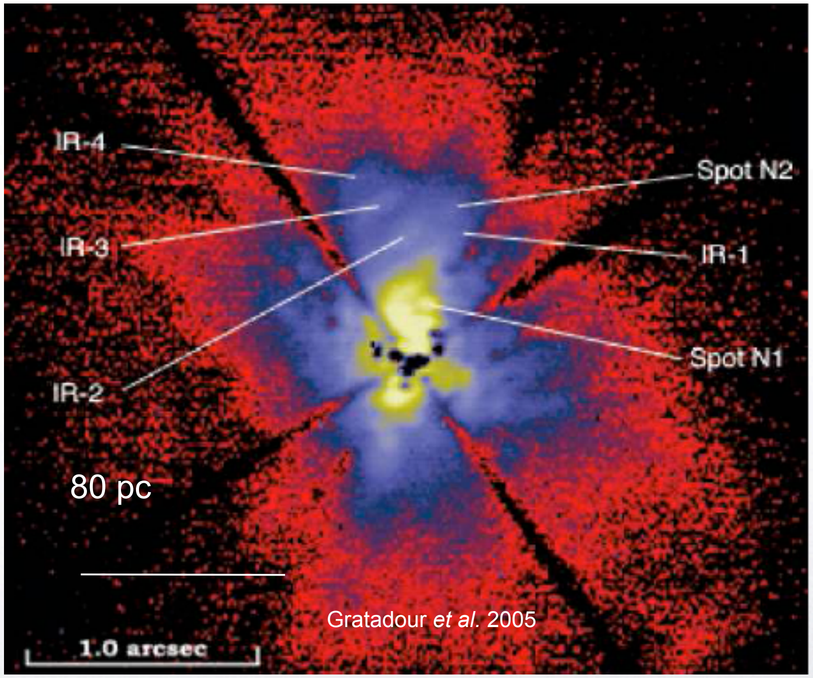
PDS 70 (Riaud, Mawet, Absil et al. 2006)

- PDS 70
  - Centaurus association (140 pc)
  - K5
  - < 10 Myr
  - WTTS
- Discovered disk
  - from 14 to 140 AU
  - $r^{-2.8}$
  - outflow up to 550 AU
- Candidate BD companion
  - M8, 2750 K
  - 27-50 MJ



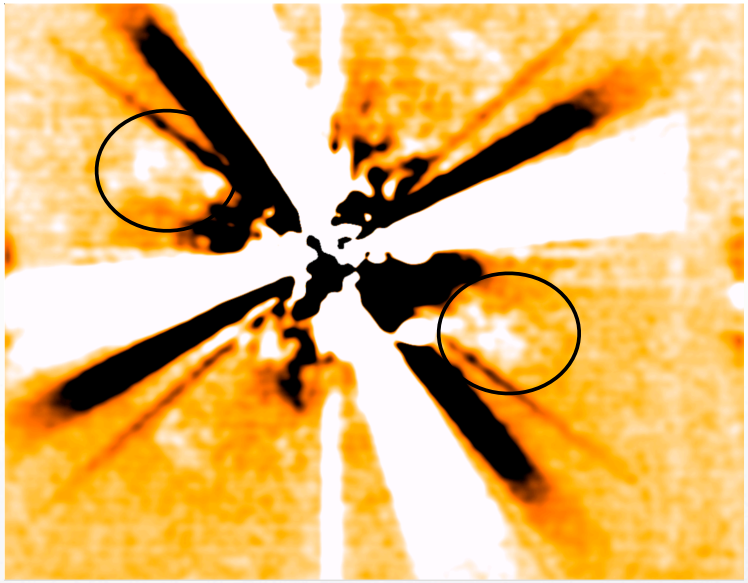
NGC 1068 (Gratadour et al. 2005)

- North: detection of knots tracing shocks induced in the ISM by the passage of the jet ; relative photometry suggests very small dust grains transiently heated by UV photons of the central source.
- To the South: a new group of filamentary structures, distributed in a cone at about 150 pc from the core. They might trace the redshifted southern narrow line region, seen through the dust.
- Larger scale (within a radius of three hundred pc): the source has an overall biconical shape whose angle matches well with the bicone observed in the UV-visible.



HD 10647 (Mawet et al., in preparation)

Star	
Spectral type and class	F8 V
Age (Gyr)	0.3 – 4.8
Effective temperature (K)	6100
Stellar Mass (solar mass)	1.1
Stellar radius (solar radius)	1.1
Stellar luminosity (solar unit)	1.2
Distance (pc)	17.35
Planet	
Period (days)	1003
Semimajor axis (AU)	2.03
Eccentricity	0.16 ± 0.22
Mass ($M_J \sin i$)	0.93



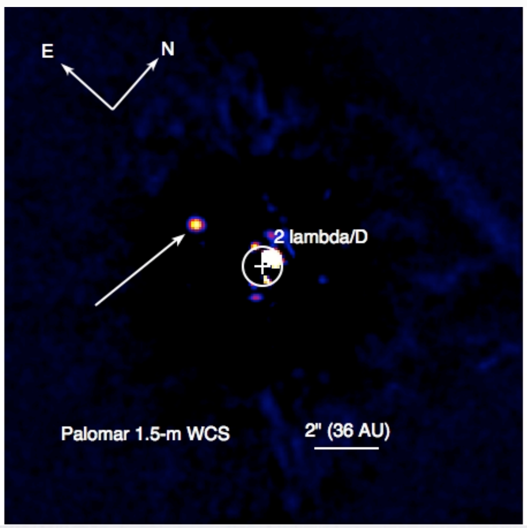
Inner disk detection (predicted by Liseau et al. 2008), completing the picture for this system.

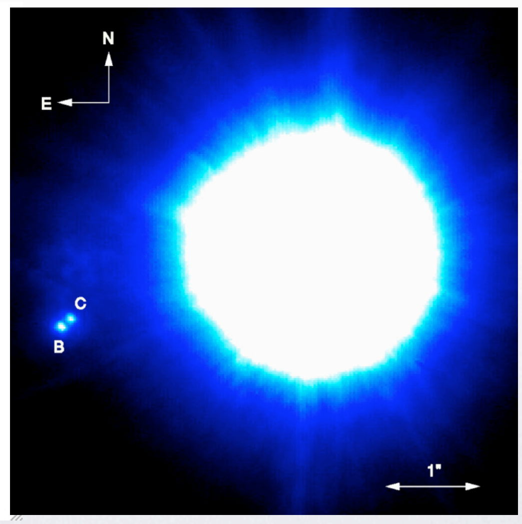
On the Palomar'VVCS with PHARO

(Serabyn & Mawet, in preparation)

HD 130948

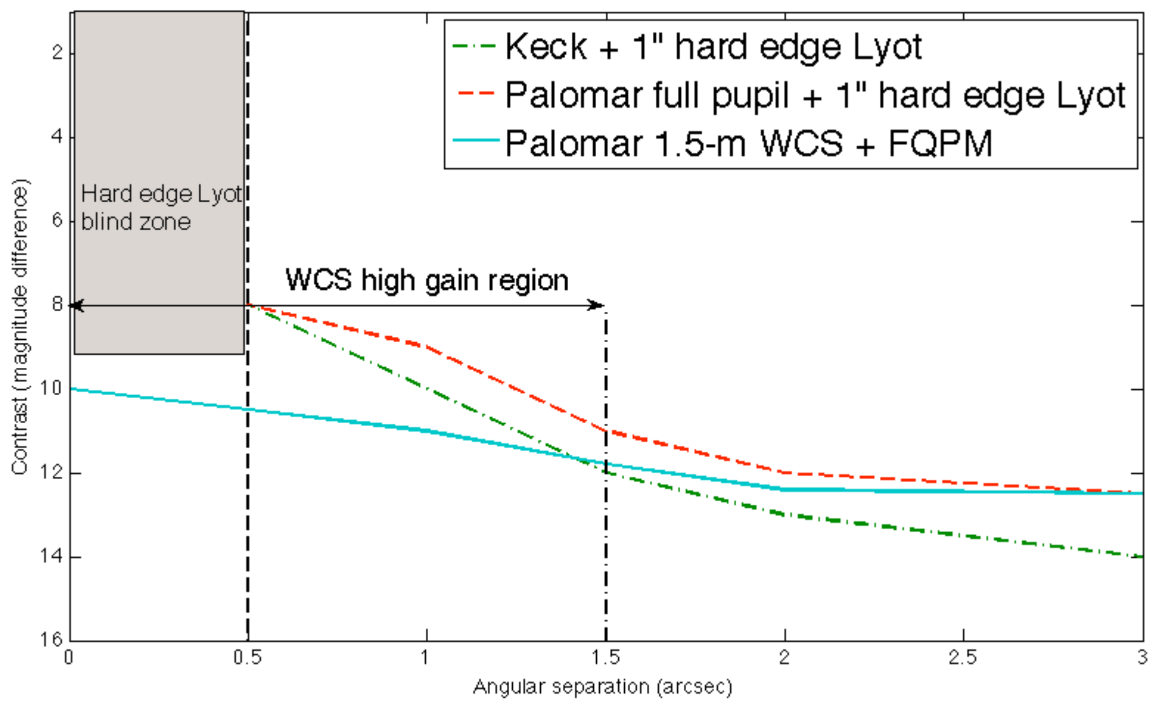
- HD130948BC (triple system, B and C are both BDs, not resolved since separated by 130 mas)
- BD pair clearly detected
- Separation of BD pair from host star: 2.61+/- 0.1 arcsec
- Delta K = 6.9 +/- 0.5
- Very consistent with earlier images
- Could have seen similar companion much closer in





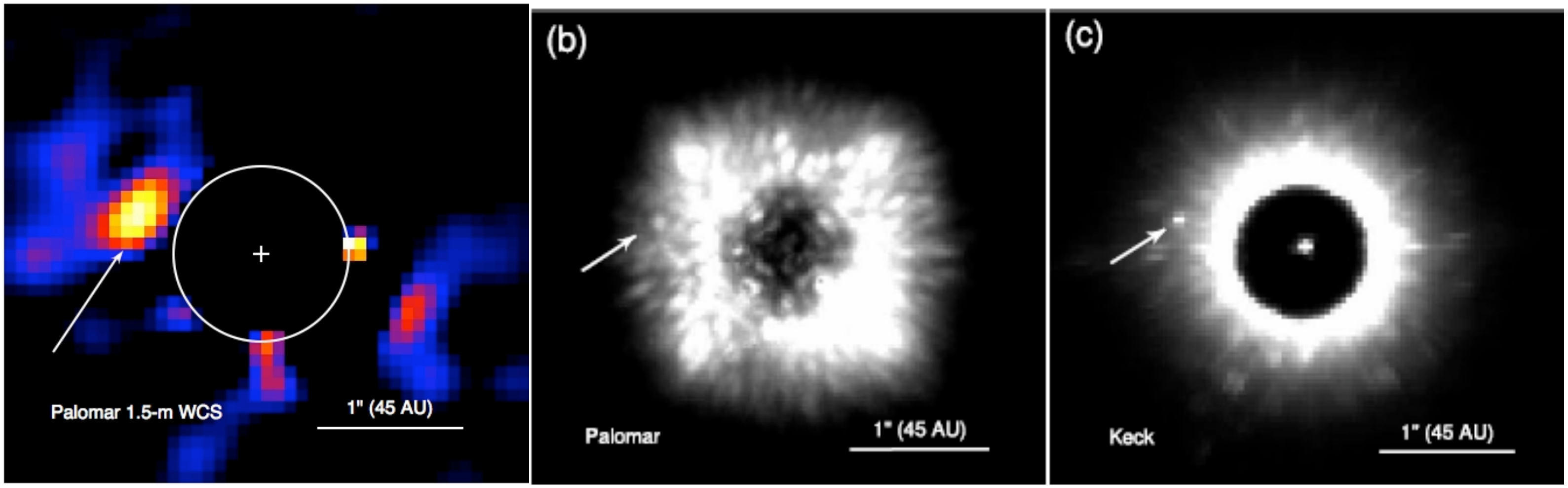
Gemini North

Detectivity

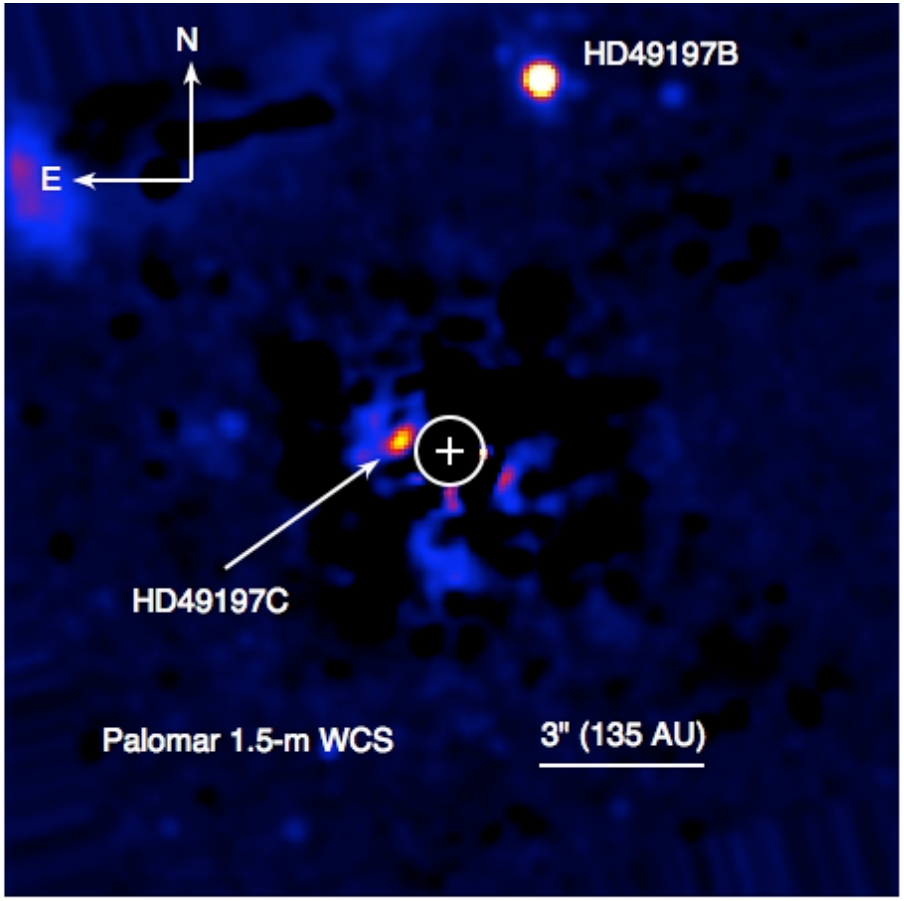


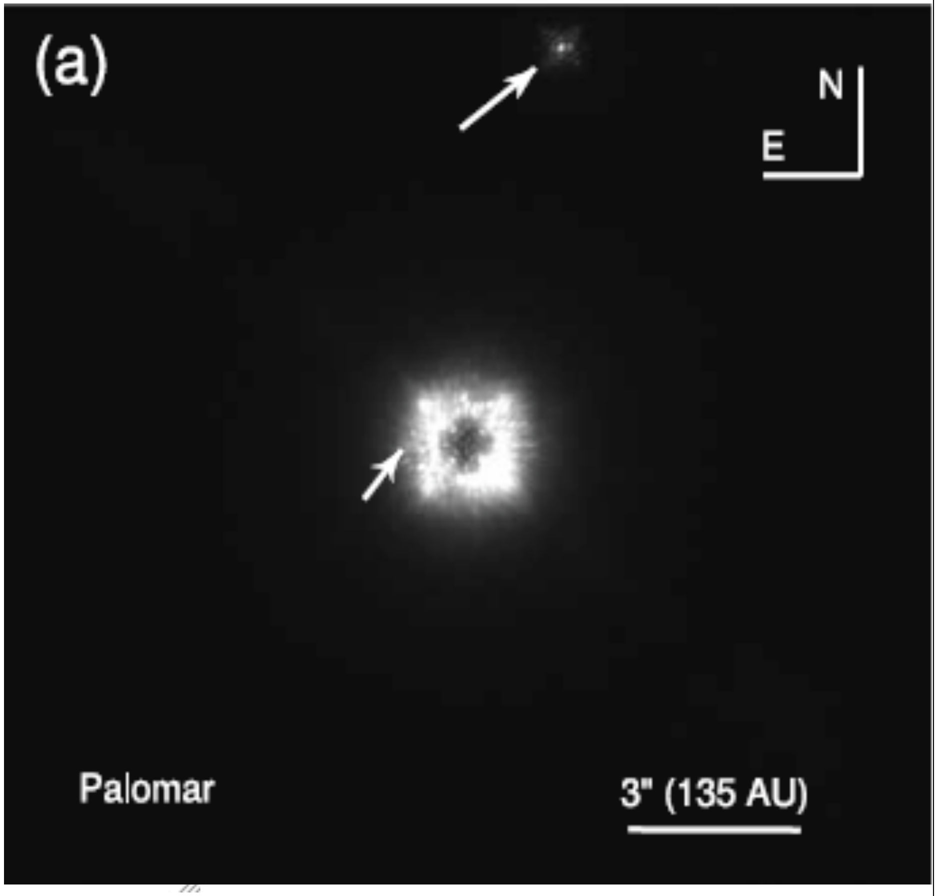
HD49197

- HD49197C seen previously at both Palomar and Keck (Metchev)
- Brightest thing in our image outside 2 lam/D is located in the right place to be HD49197C.
  - Only a few other fainter things present (how much fainter?)
  - Seems to be a reasonably solid detection
  - Residuals inside of 2 lambda/D make that region suspect.
- Measured properties for HD49197C (our resolution is 3x worse at least):
  - Separation 0.95 " +/- 0.1 = ~ 2.5 - 3 lam/D
  - Delta K: 7.7 +/- 0.8 (polluted)



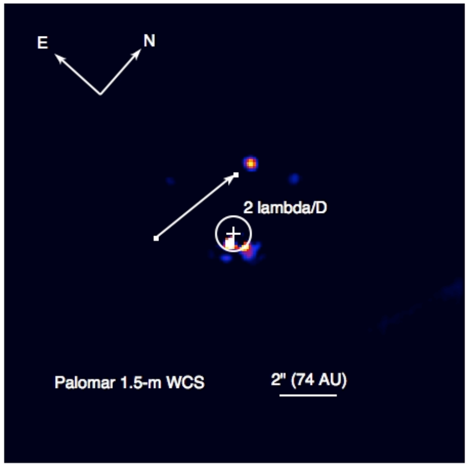
HD49197: same scale and PA





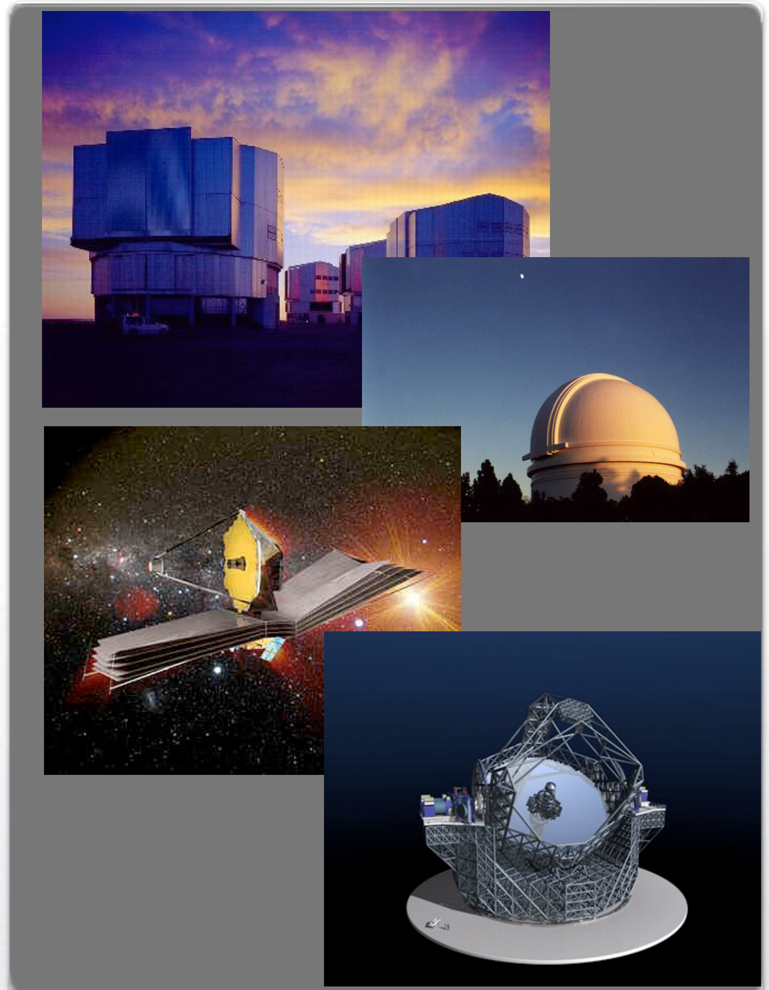
HD171488

- Interesting detection:
  - Our measurements:
    - Separation: 2”.7 +/- 0.1
    - Delta K: 6.4 +/- 0.5
    - Potential companion?
      - Is del-K of 6.4 a bit bright for a BD? (or is this a young enough star that BDs are brighter? Or a background object?)
  - Could have been missed by McCarthy et al. 2004 since their Lyot spot radius was 2”.5
  - Check if more recent surveys looked at it; McCarthy data on this star from summer 1995?



Some perspectives

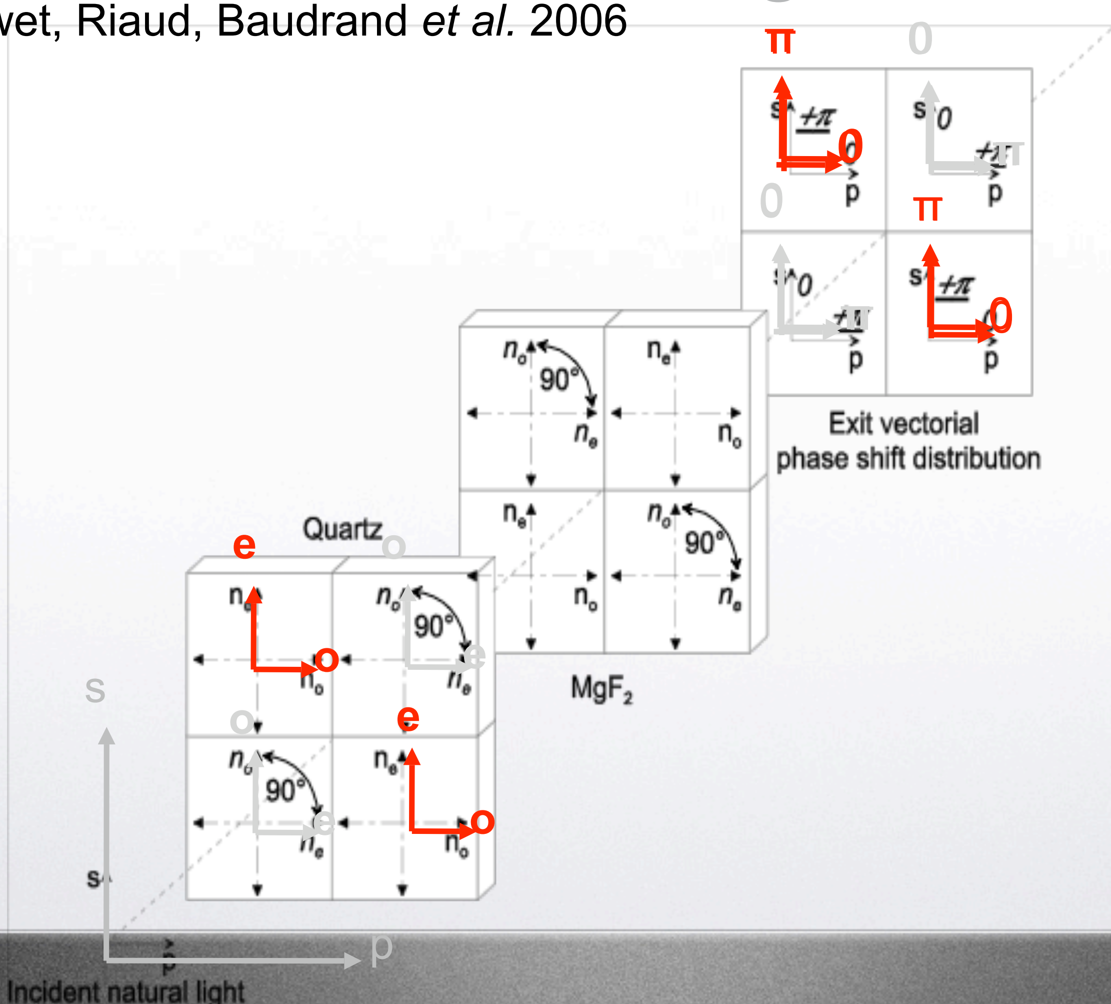
- SPHERE (VLT): prototype manufactured, technology validated
- Under integration in MIRI (JWST)
- Palm-3000 (Palomar)
- Under consideration/development for:
    - METIS (N band, VLT)
    - EPICS (JHK-band, EELT)
    - a Gemini/Keck/TMT WCS (Mawet et al. 2008) ?
    - ACCESS (space-born telescope)



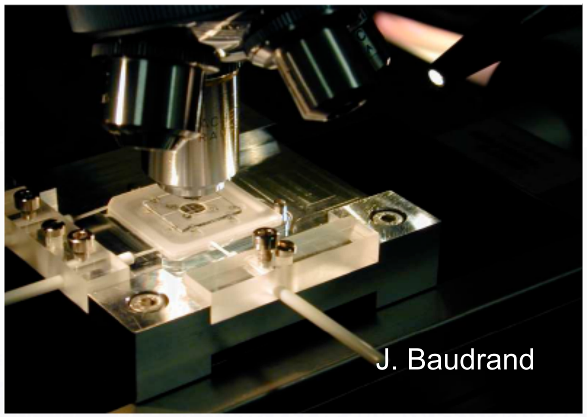
Evolution of the FQPM

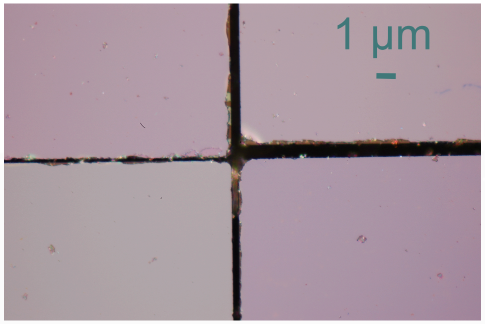
Achromatic FQPM using halfwave plates

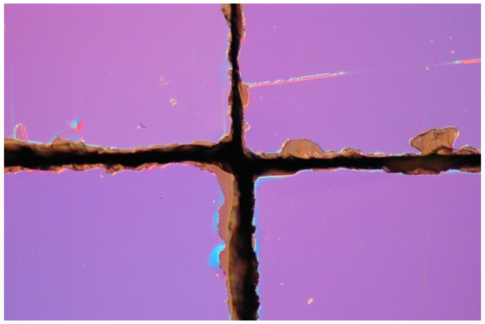
Mawet, Riaud, Baudrand *et al.* 2006

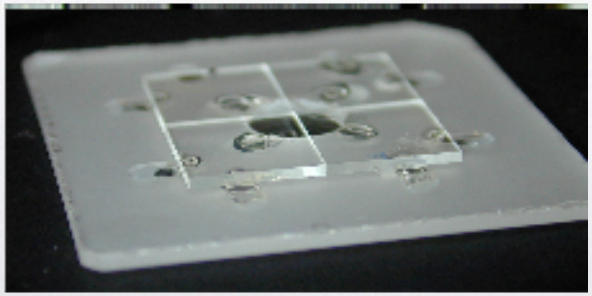


HWP FQPM



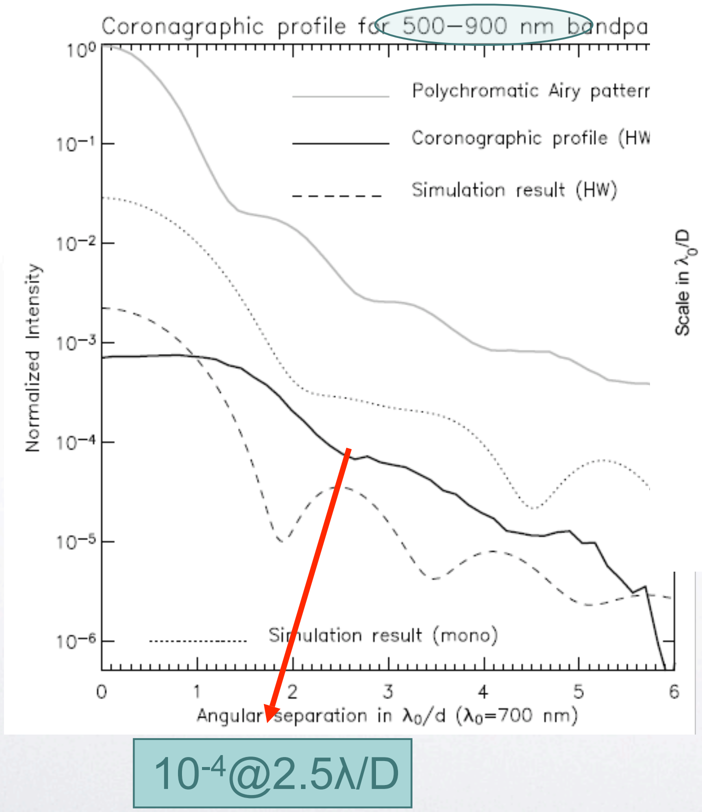


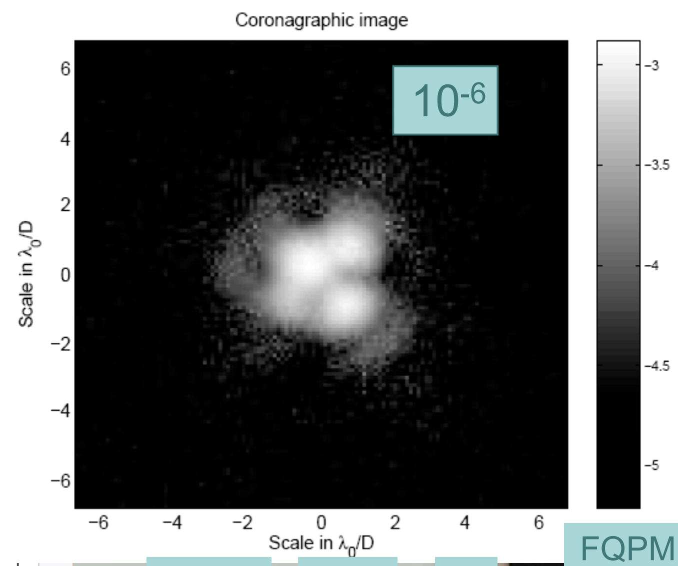


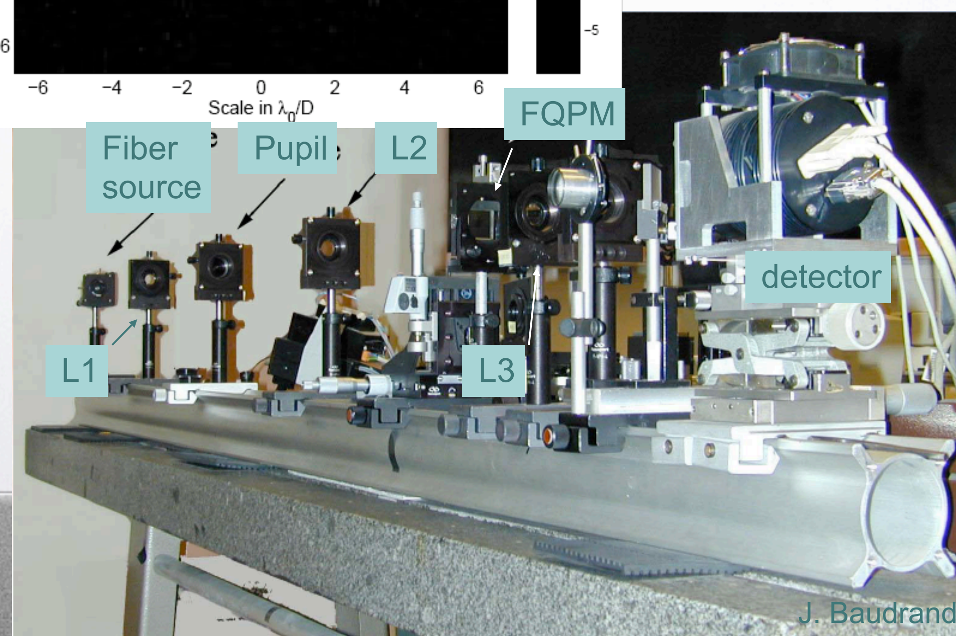


Cutting
Polishing
Assembly
very delicate (micron level)

Lab results in the Visible

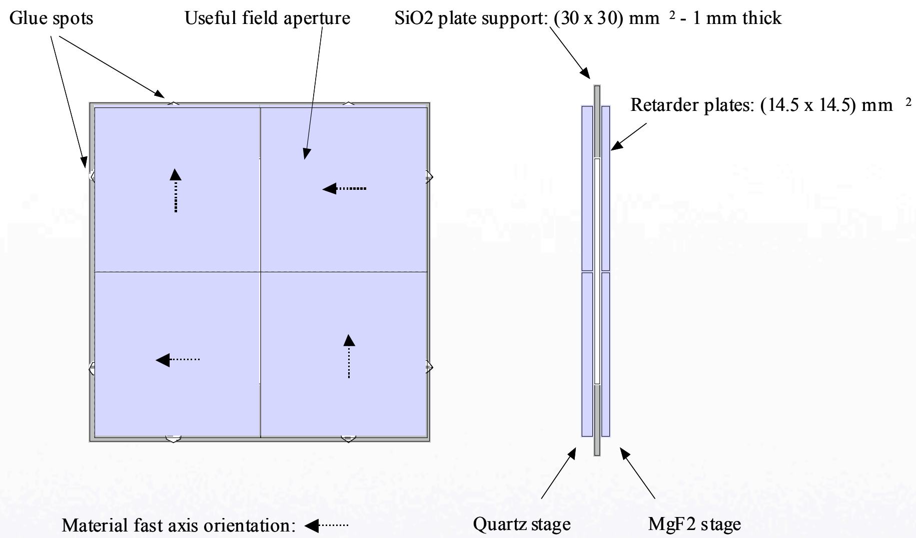


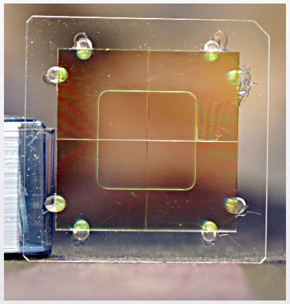


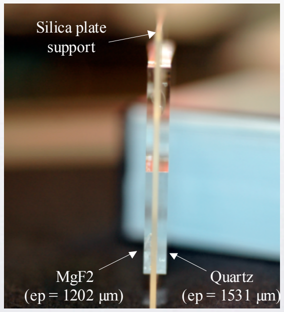


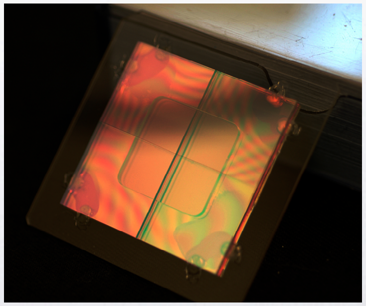
Technique chosen for SPHERE

Boccaletti et al. 2008

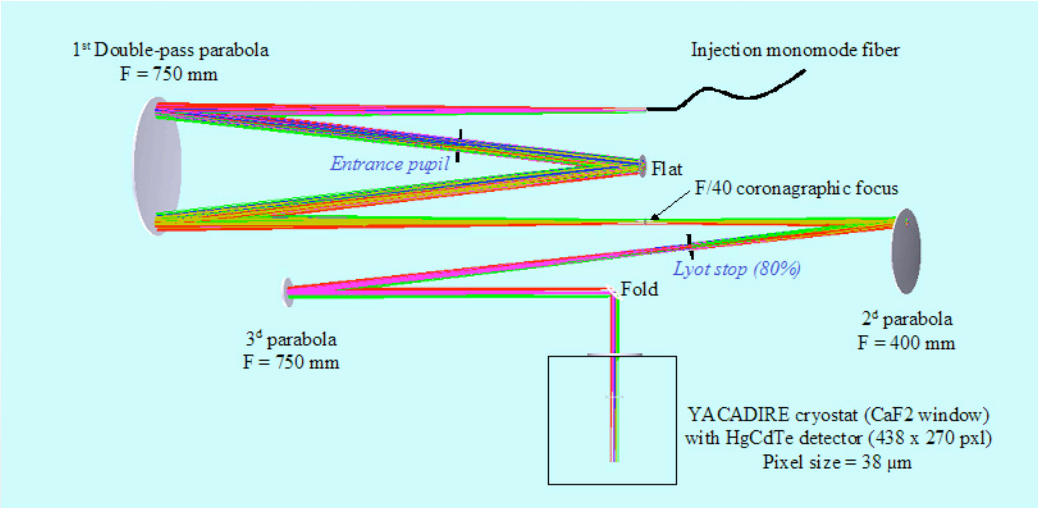


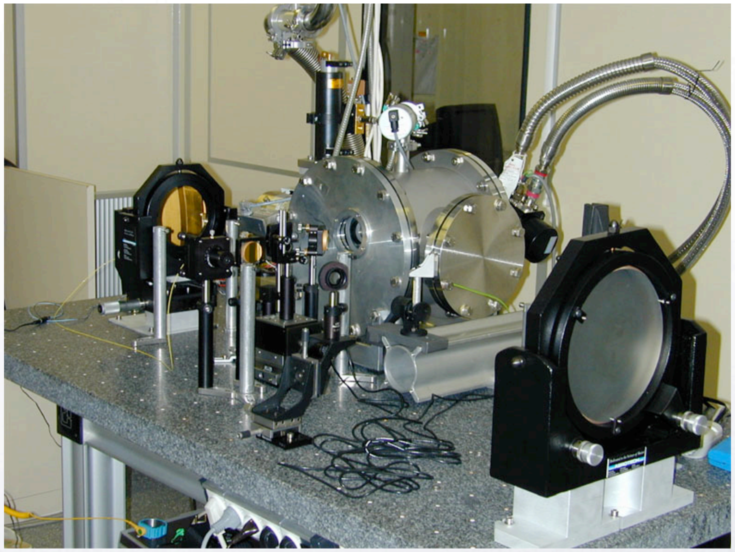




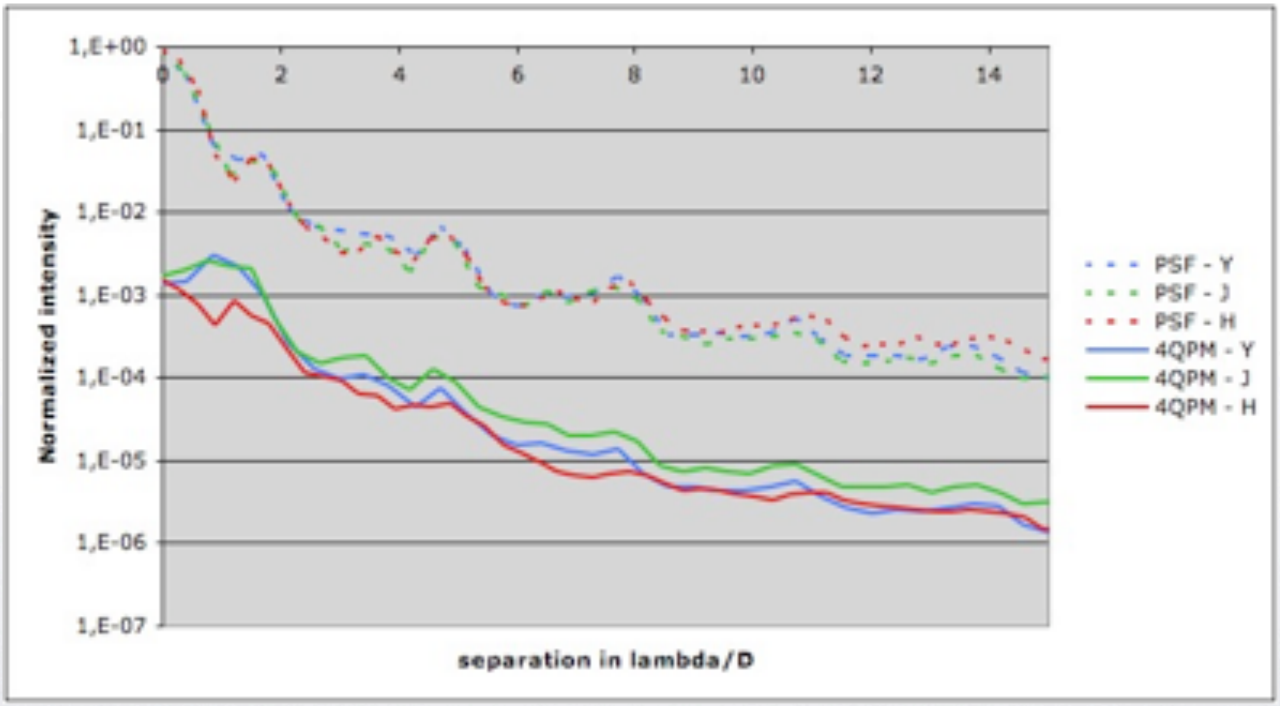


SPHERE coronagraph testbed



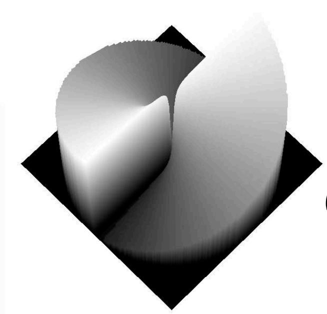


Test results

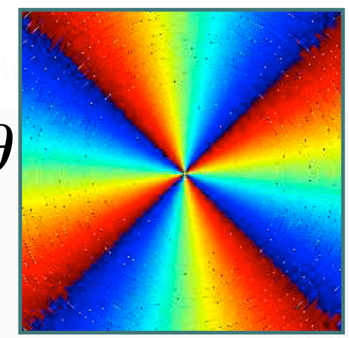


Optical Vortex

Phase screw dislocation

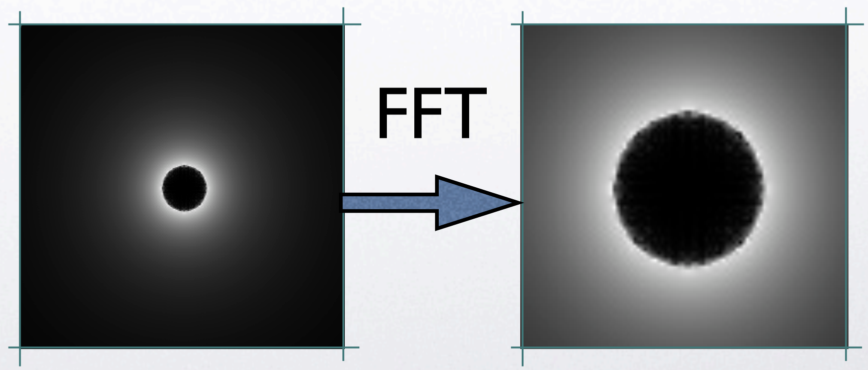


$$e^{ilp\theta}$$



= singularity on the axis
→ destructive interference

→ « black hole »
= optical vortex

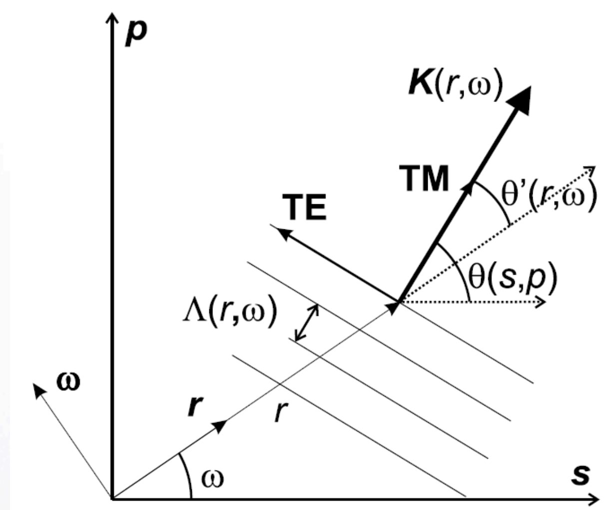


Vectorial vortices

- Pancharatnam

  (or geometric) phase

  $$\phi_p = \arg \langle E(\omega, r), E(0, r) \rangle$$



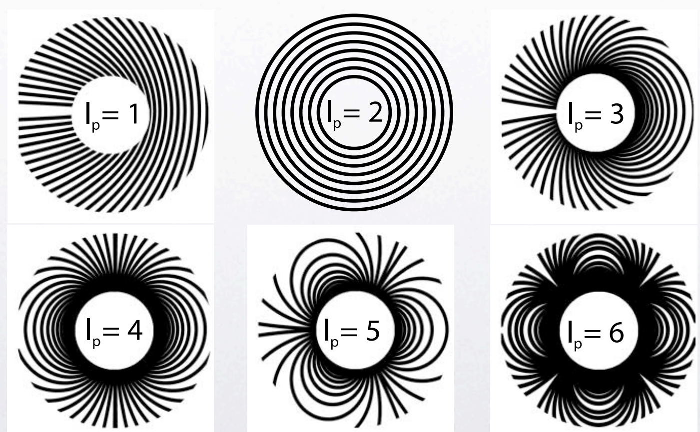
- Topological charge

  $$l_p = \frac{1}{2\pi} \oint \nabla \phi_p \, ds$$

- Jones formalism, natural light can always be decomposed in 2 orthogonal incoherent polarization states

Pure vortex term

- Vortex: $e^{ilp\theta}$
- Geometric phase => achromatic
- Topological charge: $\theta = l_p\omega/2$



Analytical treatment: perfect rejection (Mawet et al. 2005, Foo et al. 2005, Jenkins 2008)

- $l_{p\,\mathrm{th}}$ Order Hankel transform of J_1 :

$$A_{\mathrm{pup}}(\rho, \psi, l_p) = -i^{l_p-1}\frac{2e^{il_p\psi}}{R_{\mathrm{tel}}}\int_0^\infty J_1(2\pi R_{\mathrm{tel}}r)J_{l_p}(2\pi\rho r)\,dr.$$

- Weber-Schafheitlin integral :

$$A_{\mathrm{pup}}(\rho, \psi, l_p) = -i^{1-l_p}\frac{2e^{il_p\psi}}{R_{\mathrm{tel}}}\begin{cases}(2\pi\rho)^{l_p}(2\pi R_{\mathrm{tel}})^{-l_p-1}\dfrac{\Gamma(1+l_p/2)}{\Gamma(l_p+1)\Gamma(1-l_p/2)}\,{}_2F_1\left(\dfrac{l_p+1}{2},\dfrac{l_p}{2};l_p+1;\dfrac{\rho^2}{R_{\mathrm{tel}}^2}\right)\\(2\pi\rho)^{-2}(2\pi R_{\mathrm{tel}})\dfrac{\Gamma(1+l_p/2)}{\Gamma(2)\Gamma(l_p/2)}\,{}_2F_1\left(\dfrac{l_p+1}{2},\dfrac{2-l_p}{2};2;\dfrac{\rho^2}{R_{\mathrm{tel}}^2}\right),\end{cases}$$

- Solution : $\boxed{A_{\mathrm{pup}}(\rho, \psi, l_p) = 0, \qquad \rho < R_{\mathrm{tel}} \text{ and } l_p = 2, 4, 6, \ldots.}$

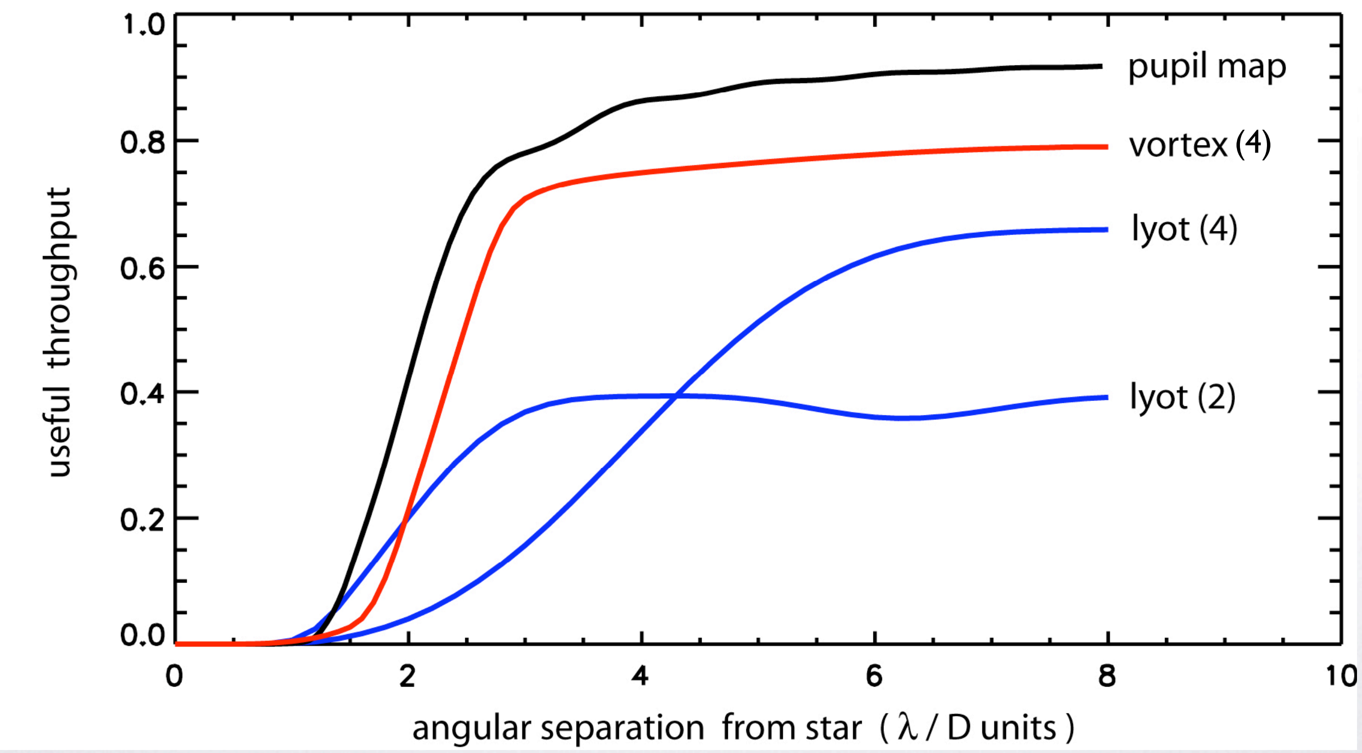
Analytical treatment: low-order aberration sensitivity

- Sensitivity to tip/tilt s : $I_2 = \frac{\pi^2 s^2}{6}$ $I_4 = \frac{\pi^4 s^4}{32}$ $I_6 = \frac{\pi^6 s^6}{240}$

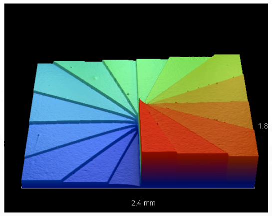
- Sensitivity to Stellar size : $\frac{\int_0^R [(\pi^6 s^6)/240] s \, ds}{\int_0^R s \, ds},$

- Exemple: R=0.01 λ/D
  => lp=2 total leakage 8 10^{-5}
  => lp=4 total leakage 10^{-8}
  => lp=6 total leakage 10^{-12}

Useful throughput



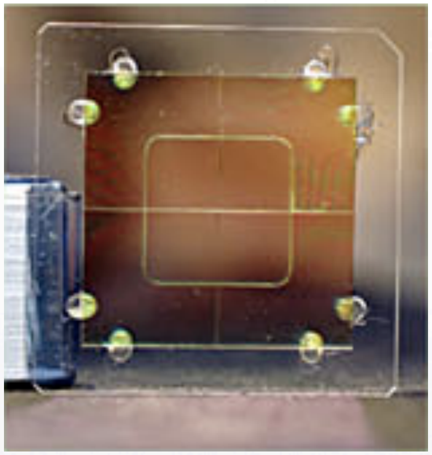
Practical implementation



- Implementation of vectorial vortices $\neq$ scalar vortices (Swartzlander et al.)
- No spiral staircase-like phase ramp
- Instead homogeneous birefringent medium with space-variant optical axis
- 3 possibilities:
  - natural birefringent crystals
  - form birefringent subwavelength gratings
  - liquid crystals

Birefringent crystals

- Solution adopted to achromatize the FQPM for SPHERE:



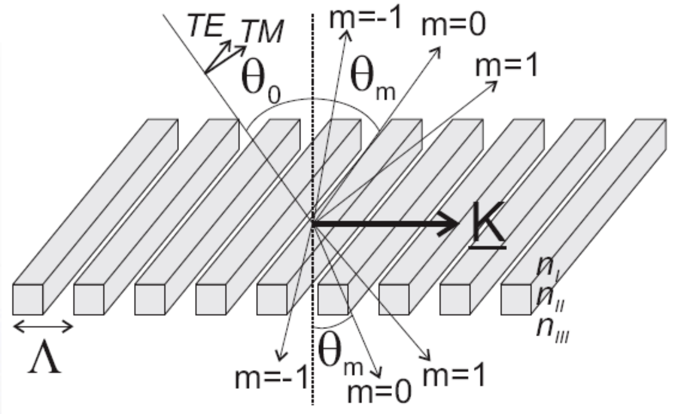
- Technology tested in the optical:
    - 10^{-6} at $5\lambda/D$, 60% BW (Mawet et al. 2006)

Birefringent crystals

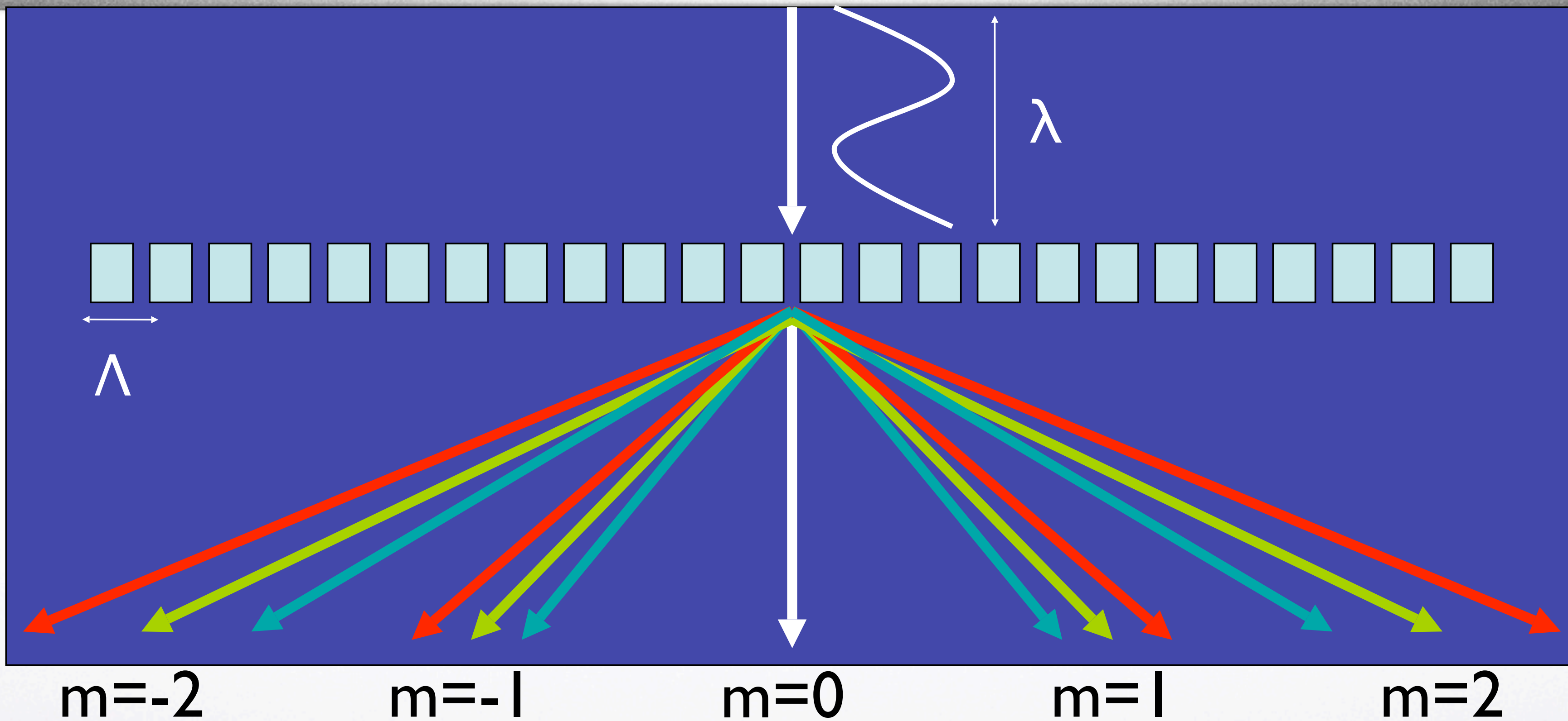
- Pros:
  - Huge bandwidth (from J to K)
  - Cost-effective
- Cons:
  - Limited contrast: 10^{-5} at 4 λ/D
  - Assembly delicate (cutting, gluing,...)
  - limited to FQPM achromatization

Subwavelength gratings

- Grating equation:

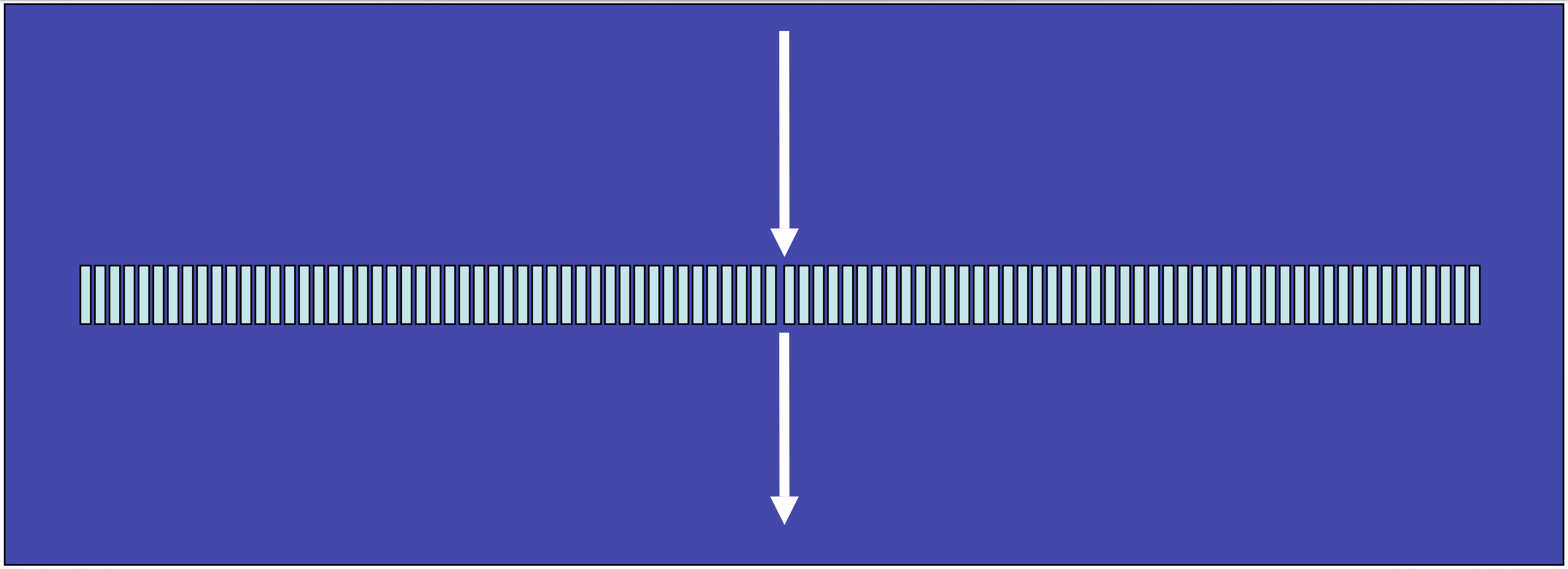


$$\boxed{n_{I,III}\sin\theta_m \pm n_I \sin\theta_0 = \frac{m\lambda}{\Lambda}}$$



Grating eq

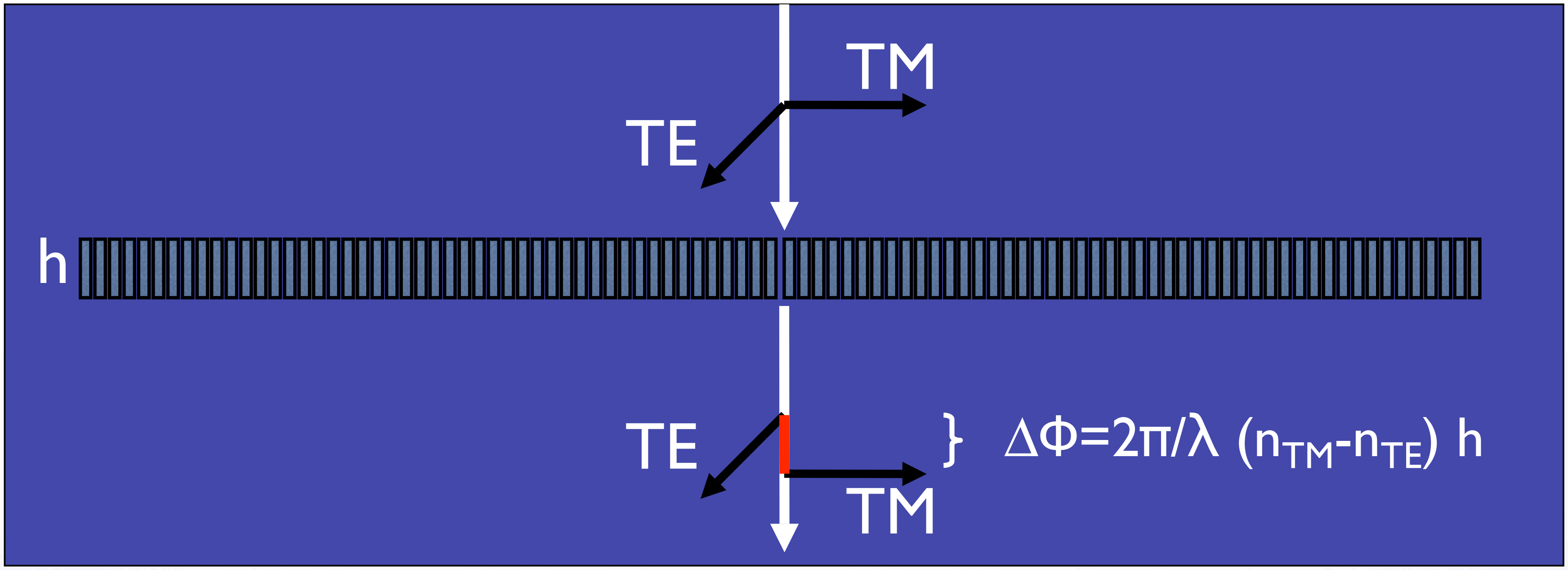
$$\boxed{n_{I,III} \sin\theta_m \pm n_I \sin\theta_0 = \frac{m\lambda}{\Lambda}}$$



m=0

Subwavelength grating (Λ<λ) = zero order grating (ZOG)

$$\boxed{\frac{\Lambda}{\lambda} \leq \frac{1}{n_I \sin\theta + \max(n_{I,} n_{III})}}$$



ZOG 1D artificially birefringent
Geometry structure control

fine tuning of the form birefringence dispersion

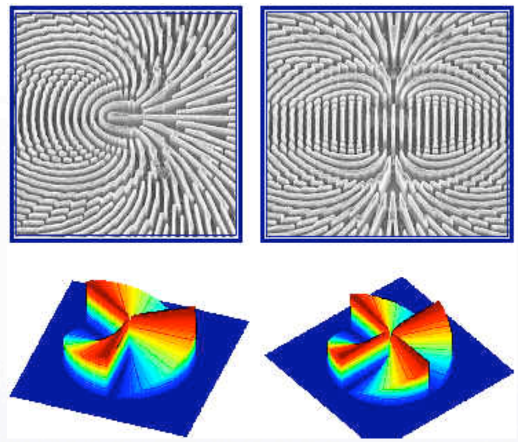
$\Delta \boldsymbol{n_{form}} \, \boldsymbol{(\lambda)=n_{TM}-n_{TE}}$

chromatism compensation

$\boldsymbol{\Delta\Phi=2\pi/\lambda \, (\Delta n_{form} \, (\lambda))h=} \, \pi$

State-of-the-art I

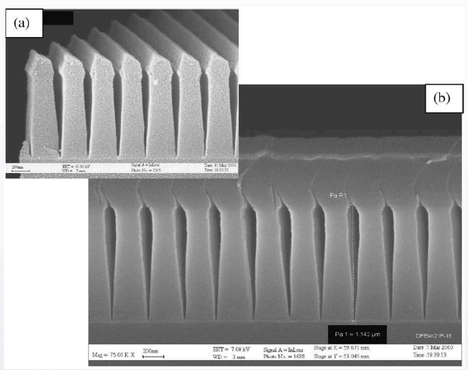
- Israel Institute of Technology at 10 microns:

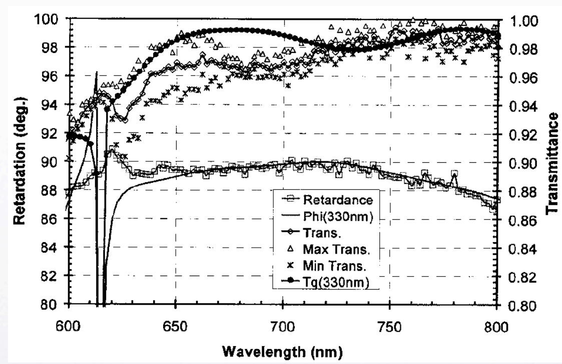


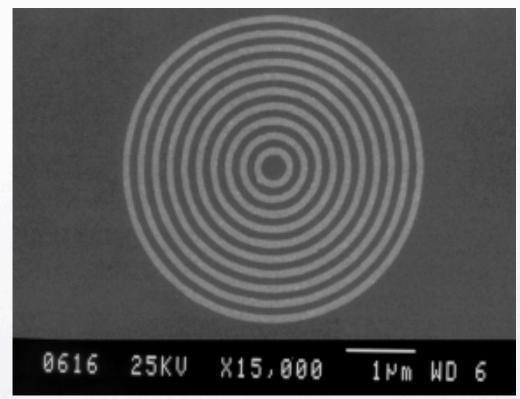
- Manufacturing of VV prototypes
- Lab demonstration VV principle (Niv et al. 2007):
    - Validation in Natural broadband light ;
    - Validation of the polarization filtering principle.

State-of-the-art II

- NanoOpto (Deng et al. 2005)
- In the optical (600-800 nm)







- Phase control: 10^{-2} rad

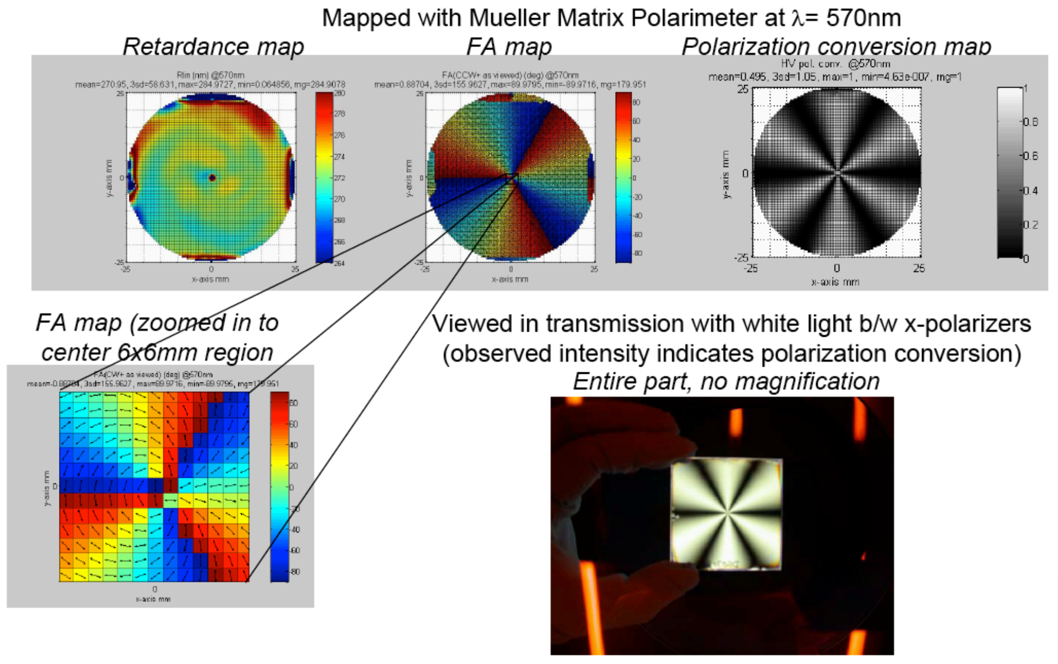
Prototyping operations

- *MicroDevices Lab:*
  - Silicon etching for K band prototype
- *MEMS Optical:*
  - Fused Silica deep etching for K band prototype
- *University of Liege, Paris Observatory, Grenoble Observatory consortium:*
  - Fused Silica for K band (SPHERE upgrade)
  - Diamond ICP-etching (with Uppsala University) for K and N bands.

Subwavelength gratings

- Pros:
  - durable, reliable
  - flexibility in the design (optical, IR)
- Cons:
  - cost # λ^{-2} (NanoOpto quote: 200k)
  - achromaticity perspectives currently limited to 10^{-2} rad over 20% BW
  - Topological charges >2 difficult to achieve with a single vortex

Technological breakthrough: Hybrid Liquid Crystal Polymers (JDSU)



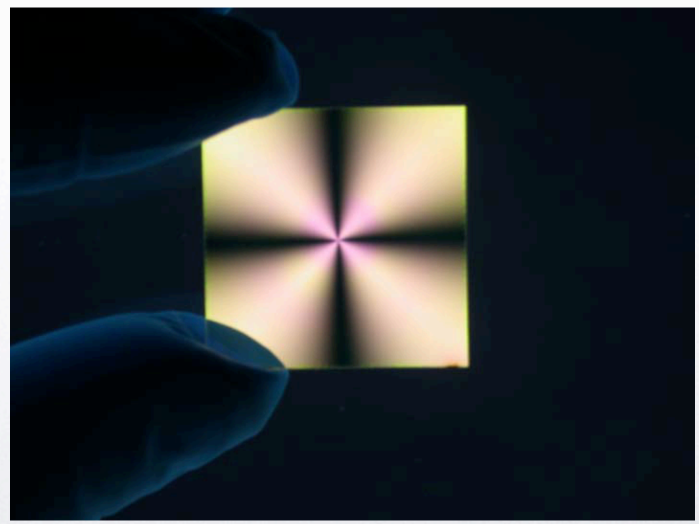
Vortex retarders produced from photo-aligned liquid crystal polymers

Scott C. McEldowney, David M. Shemo, and Russell A. Chipman

Optics Express, Vol. 16, Issue 10, pp. 7295-7308

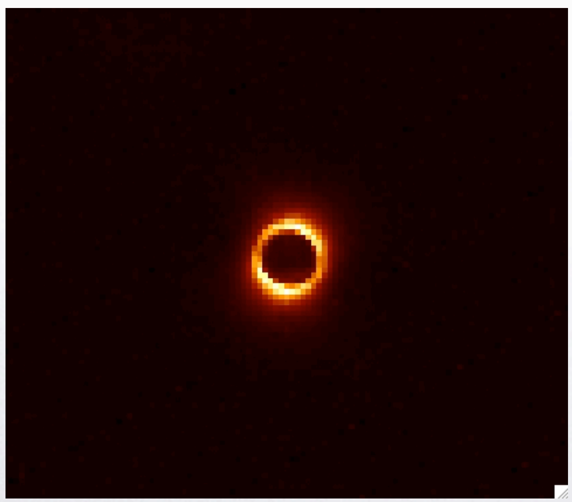
Prototyping operation

- One lp=2 single-layer H band prototype has been manufactured by JDSU and is under test at JPL (Gene Serabyn's nulling lab).



Successful first demonstration

- First results promising, demonstrating the validity of the Optical Vectorial Vortex principle and of this brand new technological approach (Mawet et al. 2008, in preparation).



Pupil plane image, showing the vortex creation

JDSU HyLCP

- Pros:
  - Lab demonstrated
  - Best achromatic perspectives
    - 1-layer design => ~0.1 rad 20% BW
    - 2-layer design => ~0.01 rad 20% BW
    - 3-layer design => ~0.001 rad 20% BW (TPF-C spec)
  - Higher topological charges easy to do (lp=8 prototype already manufactured)
  - Cost-effective

- Cons:
  - Central confusion zone (currently 50 microns)
  - reliability ?
  - space qualification ?

Conclusions - FAQs

- Vortex analytical theory shows that only ***even*** topological charges are coronagraph candidates (theoretical perfect attenuation)
- The FQPM is a discrete vortex (charge 2)
- 10^{-10}, achromatic contrast will be HARD in practice with all pure phase masks
- OVVC has the same optical net effect as the OVC, the difference is in the practical implementation of the phase shift (no phase ramp)

FAQs

- The sensitivity to aberrations scales as the power of the topological charge:

A lp=4 OV(V)C is equivalent to a BL4